GAS TURBINE COMPRESSOR BLADE TIP CONTROL USING
SHAPE MEMORY ALLOY RINGS

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Dr. Mac Schetky from Memry Corp. was asked to come forward and debrief us on work that he's doing on shape memory alloy rings which are being developed to provide a seal to reduce leakage in a T55 axial compressor.

Well, you heard mention of smart structures as applied to turbine compressor blade clearance control, so I will show you a smart piece of material. This is a shape memory alloy which if you look at it in one way, can be considered as a material with in a negative coefficient of expansion. I'll discuss how one can use this kind of behavior to control tip clearance in this small gas turbine. Smart materials have had a lot of support and notice in recent years by Air Force, Navy, DARPA and NASA. They're proving very useful for control of noise vibration and more recently for actually controlling the shape of aerodynamic surfaces so you can change the flight characteristics of a wing, or, another case, the performance of the rotor on a helicopter by changing physically the shape or orientation of the structure. You will also hear later about micro-mechanical devices, MEMS, which employ another shape memory thin films and/or piezoelectric materials to produce small motions. Other materials used in smart or adaptive structures include magnetostrictive and electrorheological systems. Now for those of you who aren't familiar with shape memory, these are alloys which undergo a martensitic transformation which is the same transformation which accounts for the hardening of steels;. the difference being that in these alloys instead of having a difference between the low temperature martensitic phase and the elevated temperature structure of maybe 1000 to 1500°F., in these alloys, this transformation takes place over a temperature interval which can be as small as 1°. This is particularly remarkable because the modulus of elasticity of these materials changes by about 350% in going from the low temperature to the high temperature phase. So you have not only an enormous change in stiffness, but the stiffness goes up with an increase in temperature unlike conventional alloys. These materials have become very interesting for use in acoustic and vibration control due to their extraordinarily high damping. The alloy shown here is in its low temperature phase, and in this form it has a specific damping capacity of up to 40%. The transformation in these alloys is accompanied by a large hysteresis; that is, temperature at which it transforms in one direction is different from the transformation from the other.

The more useful feature of these alloys is their shape memory; when a shape memory alloy in its low temperature, martensitic, condition is deformed a significant amount, the deformation is retained until the alloy is heated. Thus, a shape memory alloy which is cooled to a temperature where it is 100% martensite is deformed, but then, when heated to the temperature where it transforms to the elevated temperature austenitic phase region it completely recovers that deformation. This is what's called shape recovery or the shape memory effect which is what we're going to be using in the device we'll be talking about. Now, as we know, the efficiency of the turbine is linearly related to the tip clearance and all kinds of methods are used to minimize this clearance. In this case we're looking at a what we call a mart ring to do the job, not by changing the dimensions of the entire casing but by inserting a shape memory alloy ring whose dimensions will change in the negative direction. That is, it will shrink as the temperature increases from the cold ambient to the higher running temperature. We impart to the ring a dimension required at the running temperature to minimize the running clearance. The ring is then expanded to provide the cold-build clearance. When the ring is heated as the turbine reaches its operating temperature it shrinks to the smaller high temperature dimension and closes the tip casing gap. . Now in the particular turbine we're looking at putting rings in the second, third, fourth and fifth stage. The rate of gap clearance curves are for a very hot to 122° F day, certainly hotter than the temperature for the compressor test. The program was originally with Textron-Lycoming and the test program was designed by that moderate temperature environment, however, just as we were getting further into the program Allied Signal Engines in Phoenix acquired the Lycoming operation and the entire operation was move to a warmer climate. So we're not sure what hot day will mean. Only last week it was 100° out there. Anyway, what we have done is to choose alloy compositions and processes them so that each ring operating temperature corresponds to the equilibrium temperature for maximum power for stages two, three, four, and five At that the temperature the ring will contract and close up the running clearance. The running clearance of this particular turbine is normally about 20 mils and the intent is in this first year to reduce that by 5 mils and this is the cross section. The casing for this particular compressor is fabricated from magnesium and as such the amount of weight added is relatively small because we are not changing the casing itself but simply adding a ring insert. The ring will be held in a radial direction by locating pins shown there or in more detail here. So as the casing reaches this temperature, the ring will undergo shape memory, shrink and close that tip gap.. We haven't yet decided on what type of seal, if any, we need to prevent back flow from stage to stage . Timing is of the ring closure is critical, we don't want the ring to shrink before the stages have reached equilibrium temperature. For this curve of tip clearance you'll see that at about 300 seconds the stage is at full expansion due to centripetal force on the blade, thermal expansion of the blade and then the thermal expansion away from the tip by the casing. At that point one assumes you've reached the equilibrium temperature and that is the trigger temperature for the closure of the ring. Now, to give an idea of the clearances we are dealing with the following table shows cold build and running clearance for this compressor. Here are the typical clearances for the T55 L7 at full throttle and we're looking at two, three, four, five and you'll see 27, 22, and 26 mils clearance. Each ring must be designed so that it has the required cold clearance dimension which will, when heated, shrink to accommodate each of these clearances. The procedure is to machine a rough forged ring to the inner diameter dimension which, when at a temperature, will provide a 5 mil clearance. We then stretch the ring that at room temperature so it now has a dimension which will be provide the required .. cold build clearance. When the ring heats up, it remembers its initial dimension and shrinks down, to the calculated value to give the 5 ml clearance. Larry Portlock, Chief Engineer at Lycoming's Connecticut plant, and still involved with the program on advance turbine studies suggested that it would also be prudent to have a rub coat on the ring ID as insurance. As such, we have a 10 mil the rub ring and that will have to be factored in the dimensioning of the ring for closure. So, because the amount of shrinkage here is very small, less than 2/10%, it makes it very tricky to get an accurate closure of the ring at that small percentage because there's always some spring back when you deform these alloys. So, what you can typically do is operate at a higher prestrain level, that is, expanding it by a greater amount, but then preventing it from closing in to far by putting in what is called bias ring. This ring is made of the same material as the shape memory ring but processed so that it has no memory; this avoids the problem of using a material with a difference in coefficient expansion. It's function is to provide an elastic constrain so that the combination of the shape memory ring and the bias will give us the required accurate closure. The way that this is accomplished is fabricate two rings which are concentric to each other and joined together by shrink fitting. The inner bias ring has a diameter which matches the required running clearance, and the outer ring is the shape memory ring which provides the ring shrinkage. These rings are very thin so they are fairly difficult to fabricate. When we make these rings, what we do is to make the initial diameter as I indicated and force it down over a tapered mandrel. We know every incremental thousandth of expansion by the slope of the mantle,. and from that can quite accurately arrive at an accurate dimension for the ring. To check the ring performance we use a high temperature oil bath in which the ring is supported on a set of six pins. The diameter change is measured with dial gauges which are fixed to the ends of quartz rods which pass through "O" ring seals to make contact with the ring OD. The diameter is measured as the ring heats and cools to confirm that the cold and hot dimensions of the ring set are accurate. The testing of this tip clearance control concept has been delayed by the required moving of the compressor test rig from Lycoming in Stratford, CT to the new location for the test at Allied Signal Engines in Phoenix, AZ. The test rig is being assembled now and so the program should soon go forward. The rings have been fabricated and we're now in the process of finalizing the machining and checking. They'll be shipped to Allied Signal where they'll be installed in the test compressor. This is a compressor driven by a separate turbine so that we will be able to independently control the performance of the compressor and get accurate values. The measurements, as you would expect, include temperature, pressure, and flow . The test unit itself is shown with the measurement probes indicated for measurement of tip static pressure, tip temperature and tip pressure for each stage. We'll also, probably place in the inner surface of the ring some sort of proximity measurement device so we can actually dynamically measure that tip clearance. So that is the nature of the program to this date. The alloy we're using on this system has what is referred to as a two-way memory. That is, on heating it will shrink down to the required connection, on cooling is expands back out again; this is a characteristic which is typical of copper based shape memory alloys. The particular alloy used for the rings is similar to an aluminum bronze, an alloy with which I'm sure you're familiar. The alloy contains copper, nickel, aluminum with small additions of manganese and titanium and it's capable of stable operation up to about 150-160° C. That's adequate for this particular test , although for long term operation in a gas turbine alloys with better elevated temperature stability will be required, at least for the downstream stages. There's a constant search for shape memory alloys which will operate at higher temperatures. The most broadly used shape memory alloy, nickel-titanium has excellent stability, but unfortunately has a maximum shape recovery temperature of 90°C,. that is the temperature at which it starts to undergo its shape change. That's obviously not adequate. Various research groups have developed some higher temperature versions of nickel-titanium. Unfortunately they arrive at higher temperature capability by adding one of three elements, gold, platinum or palladium which makes for a very expensive alloy. The international shape memory research groups have carried out a broad range of research on this problem and have come up with some titanium-nickel alloys modified by hafnium and zirconium; these seem to have potential for stable higher temperature operation. . But for right now all of our rings will be made out of the copper base shape memory alloy. For this purpose we have perfectly adequate stability.

Questions

Q. I have one comment and one question. The comment is, the shape memory alloy is for shape control. It has no damping gradient okay. It does no damping.
A. In this application, no. Because the damping occurs when it's in its low temperature martensitic condition. At that point you have this 40 or 50% specific damping capacity. But once it moves to its high temperature, and here's an example, this alloy ring will like a bell and at the low temperature sound like a piece of wood. We're not considering the damping characteristic here because, as I indicated, these alloys have a dramatic and remarkable change in .modules, and, unfortunately, in the low temperature martensitic condition the modulus is only about three and a half million psi..

Q. The question I have is the heat transfer issue. In two way shape memory alloy you need the heating and cooling. How are you controlling the heating and cooling. Are you using the gas in the flow?
A. The assumption is as follows: in the present turbine compressor section they have a steel rub ring inserted in the casing. What we're doing really effectively is taking out that steel rub ring and replacing it with the shape memory ring. The closure of the tip clearance was shown to take place in about 300 seconds, typical of that particular geometry with a steel ring. So the assumption is that the steel or shape memory ring heats at about the same rate as the casing. And so the performance in terms of heating rate is due solely to the gas flow past that surface.

Q. In a conventional actuator we use an electric current to heat up the shape memory alloy, could this be used.
A. Shape memory alloys can be heated electrically, but also there are many cases where they are heated by gas flow or by fluid flow. The alloy doesn't care how it reaches this temperature; when it reaches the transformation point the shape change takes place.

Q. But how do you control the heat to supply to the shape memory to change in shape?
A. You don't control, what we're saying is that starting from the initial cold temperatures stage two, three, four, or five, reaches the temperature typical of the operating temperature for that stage the ring will have started to heat and the diameter closed down. But this is at some specified cruise or full power condition. We don't at this time attempt to control the heating rate. For a normal operating temperature, the ring is designed to be fully closed at that temperature. Now keep in mind there is a window there because that operating temperature is going to vary with power. What we're doing now is demonstrating the principle using what's an available performance curve for that turbine. So we will be comparing that turbine in its present condition and then we'll put the clearance control rings in and we'll have a direct one to one comparison with performance.

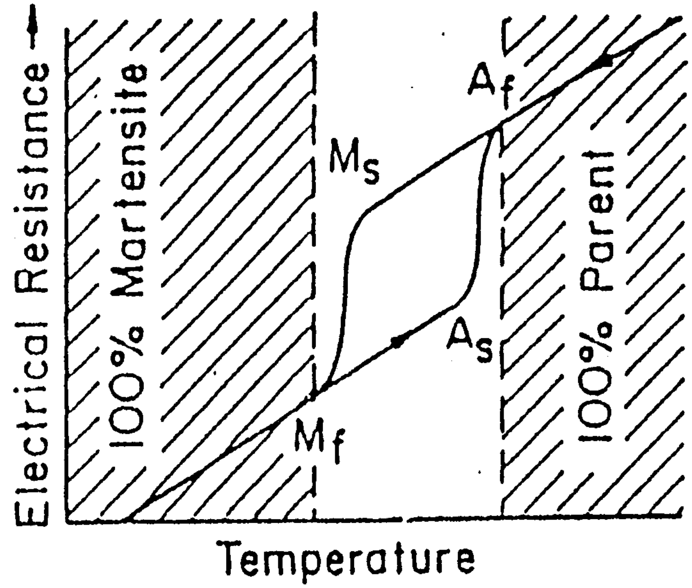
Q. I have two questions. The first one is how are you going to handle deterioration in cycle temperatures? And the second question is for an aircraft engine application we need open clearances at takeoff for the rotation condition, so how are you going to handle that?
A. Well, the first question , some shape memory alloys have cyclic instability in that they, after a number of cycles they change their transformation temperature. That is certainly true of the copper zinc aluminum alloy, less true of the copper aluminum metal and it's not true of the nickel titanium modified with copper which has very stable cyclic performance and is capable of temperature excursions up to 250°C. The problem with that alloy is simply that the transformation temperature is too low, but we may find a way of using that type of alloy since it is very stable in terms of cycle stability. We've cycled these alloys to over 250,000 cycles with no change in transformation temperature.

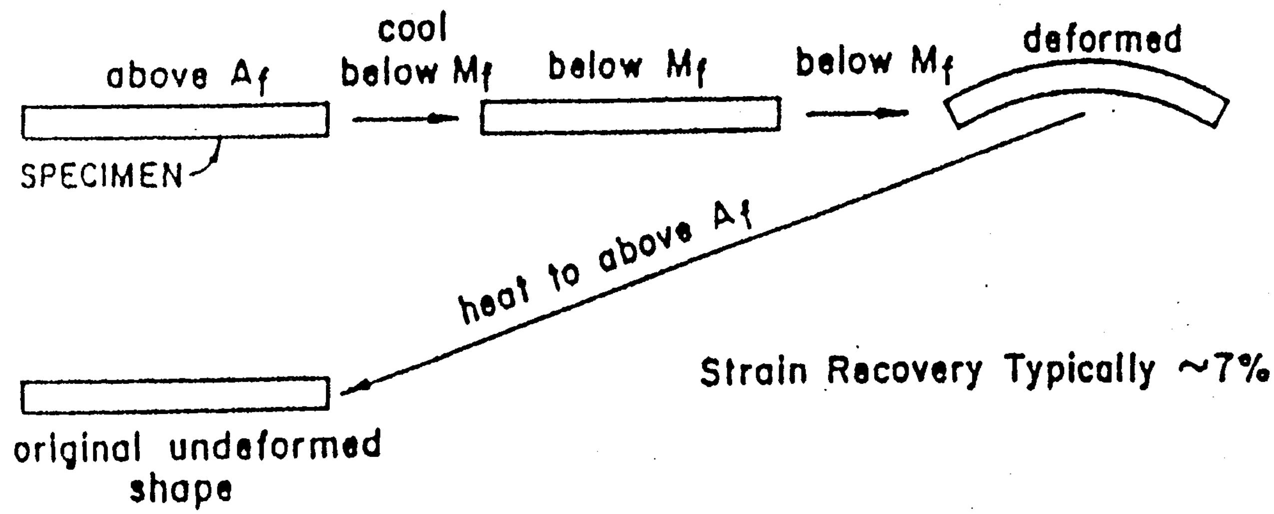
Q. The question I had was, the deterioration you may also be talking about is erosion. Was that the condition?
A. We were talking about transformation temperature stability. We have no information on gas erosion.

Q. I'll try my question again. In this engine it self, we have over the life of the engine a deterioration in temperature. That is, that given operating condition the engine runs hotter. Now, how do you handle that, because it can be quite significant. For example, today's CPM 56 engine is probably going to go into service initially with EGT margin of 150° F. So how do you handle that with this device?
A. Well, we have not addressed that at this point. Our first will be using a specific base point given inlet temperature and components in what is effectively refurbished a new condition. So we haven't accounted for degradation or a change in that over life, but that's certainly something that has to be addressed.

Q You're using it as a passive way so you are not using the capability of an active element. It's an active element, that's why we use electric heating.
A. Yes, in that sense it is passive. It's responding to the environment and adjusting its dimensions in reaction to this externally variable..

Q. Now I'd like to ask you a very big question. When you put these rings inside the housing, you are fixing them to the casing circumferentially but as soon as you heat the housing is going open up and the rig is also going to open.. So we have develop a big clearance between the casing and the blade tip. How can you assure after all this was connected to the rotor, because it looks like the ring is just floating.
A. The calculations that I are made on the basis of the existing steel ring practice. They have a steel ring supported by six pins and the rings stay concentric. The assumption is with tight clearance on the holes and pins that it will stay concentric. The ring supported by the six pins can move radially but not off center because of constraint if there are six pins.





Strain Recovery Typically ~7%

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Metal temperatures at steady state maximum power, hot day (122°F), SLS

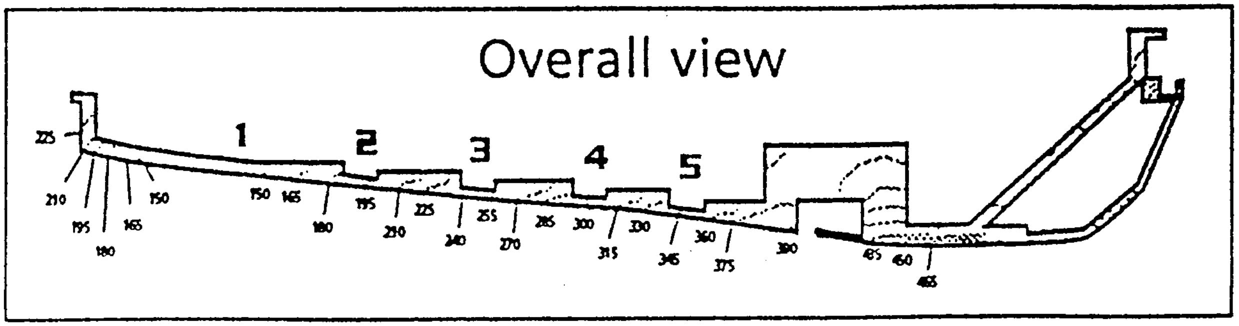
Engine conditions

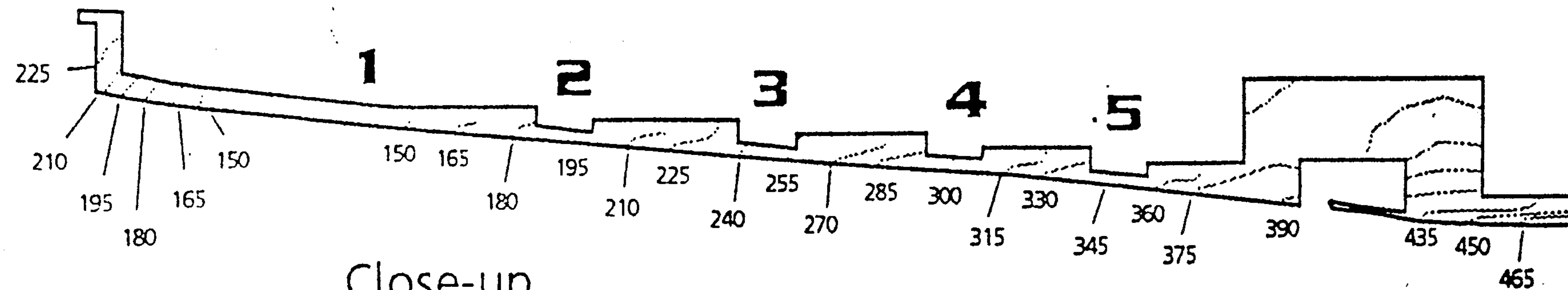
$T_3 = 695\ °F$

$P_3 = 120.53$ psia

$N_1 = 19{,}534$ RPM

$W_{ae} = 25.257$ lb/sec





Close-up

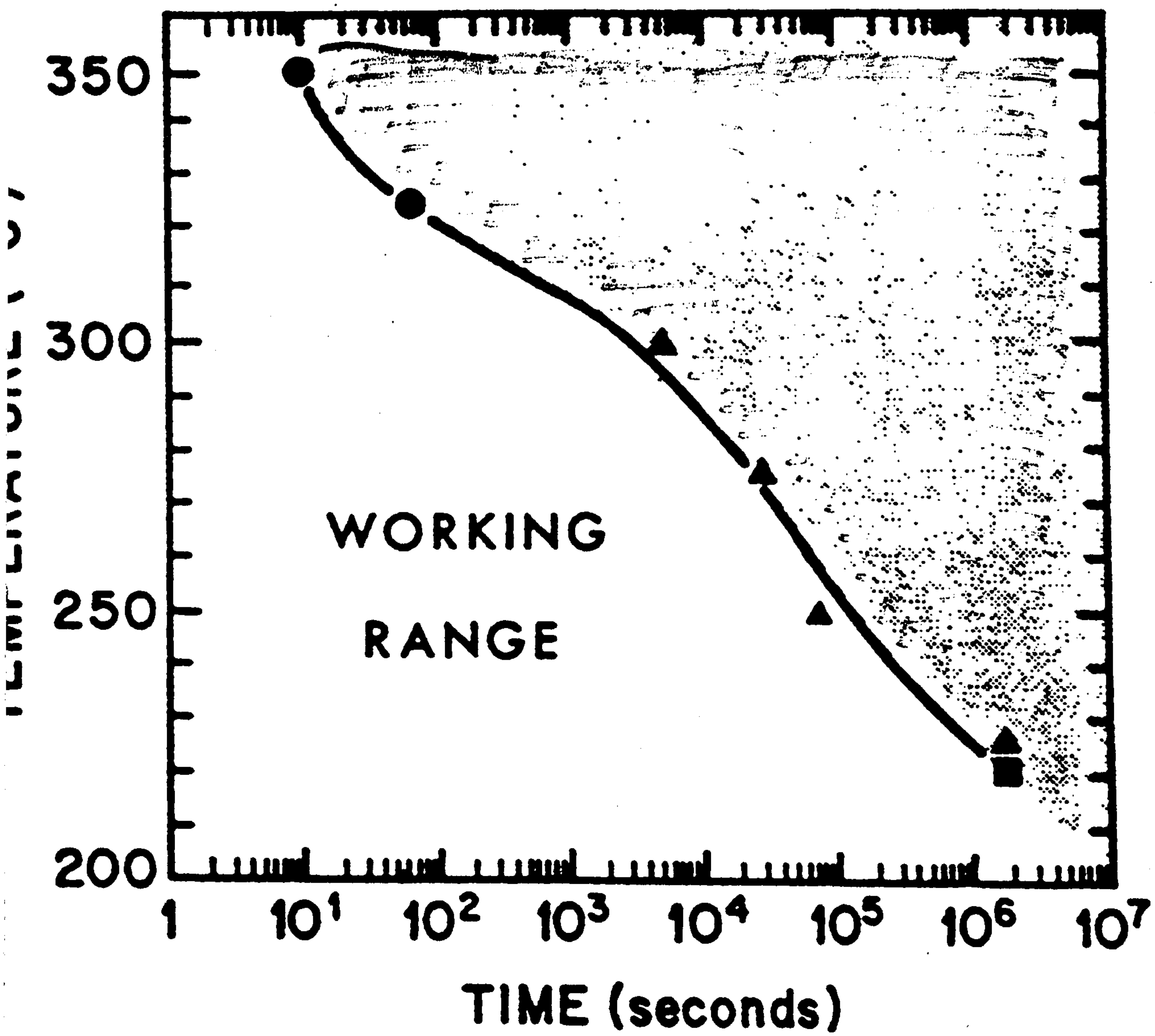
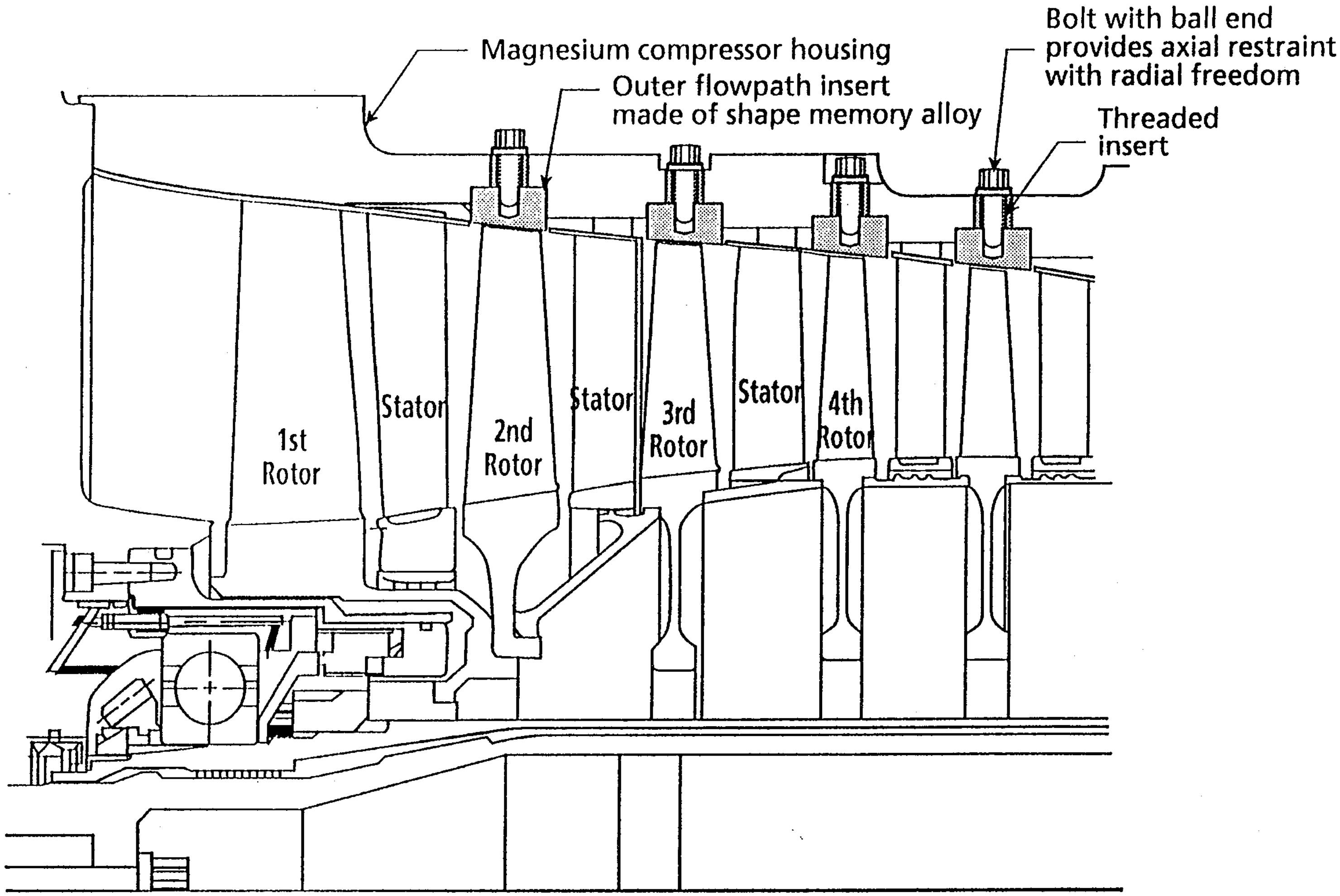
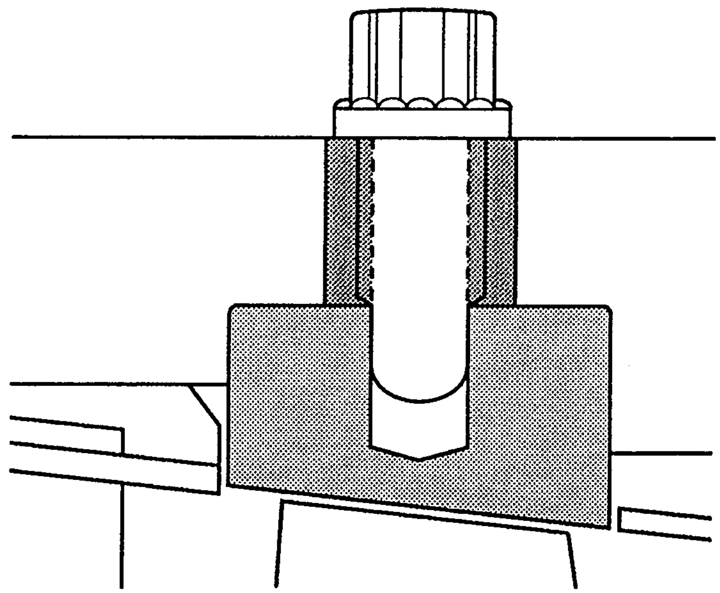


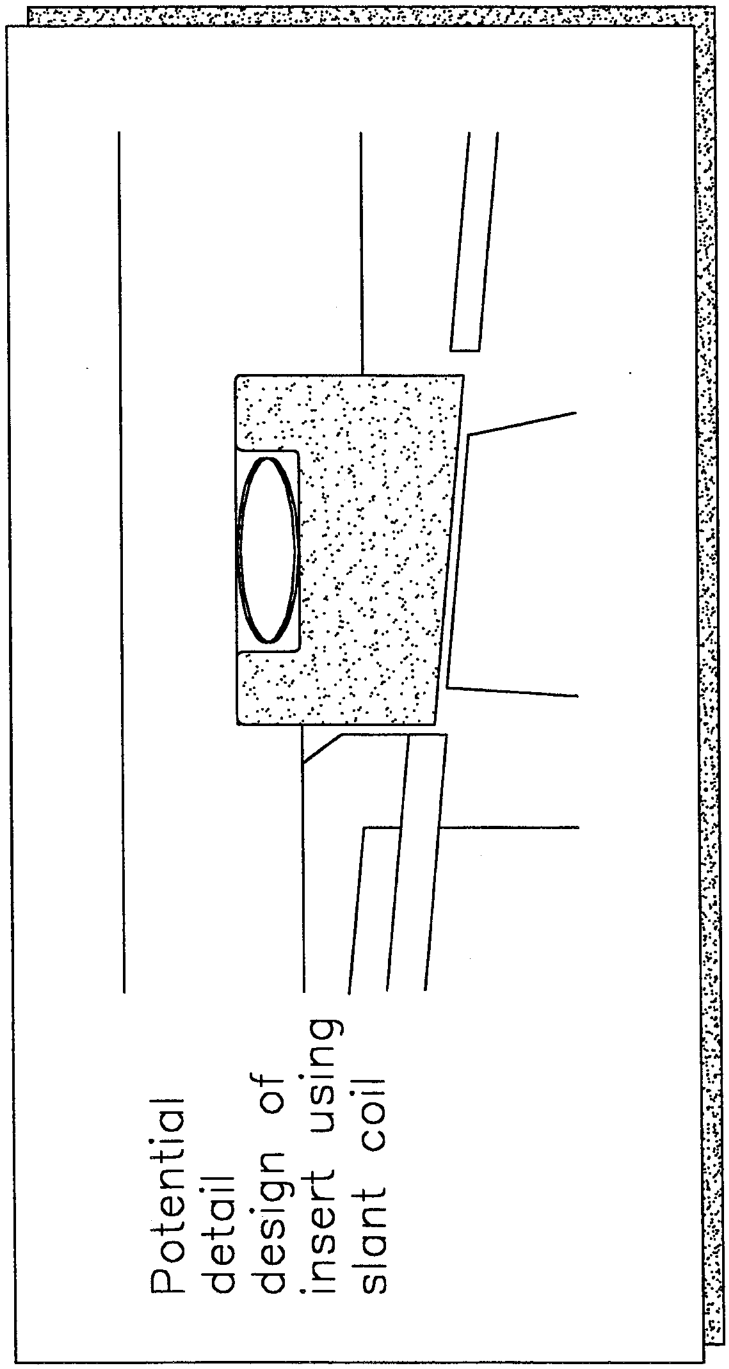
Fig. 4 Aging Stability of CuAlNi Showing Limits for Transformation T,●, Two-way Shape Memory▲, and Switching $T = [A_F - A_S]/2$ ■

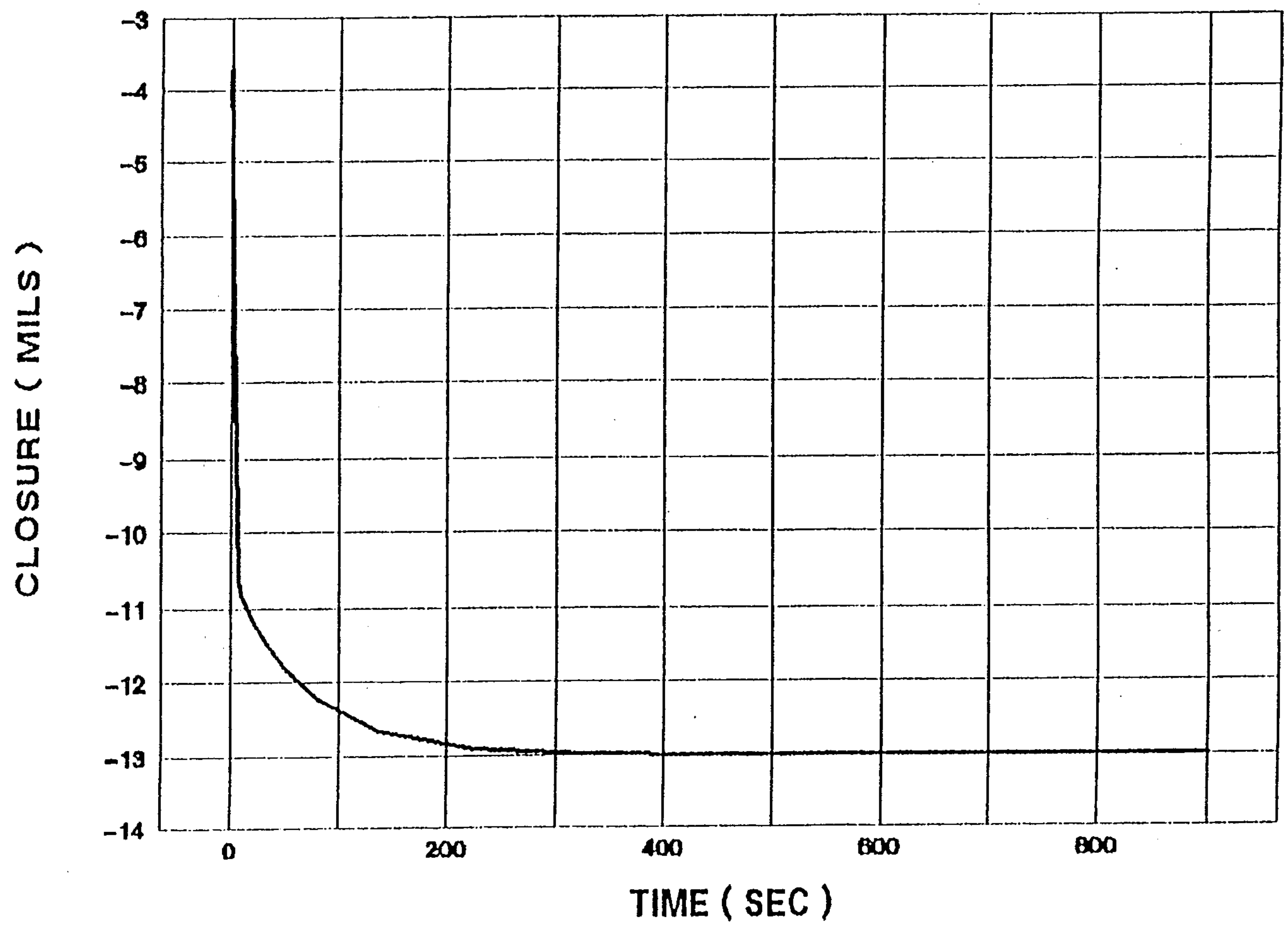
Compressor Cross Section



Potential detail design of insert




Potential
detail
design of
insert using
slant coil



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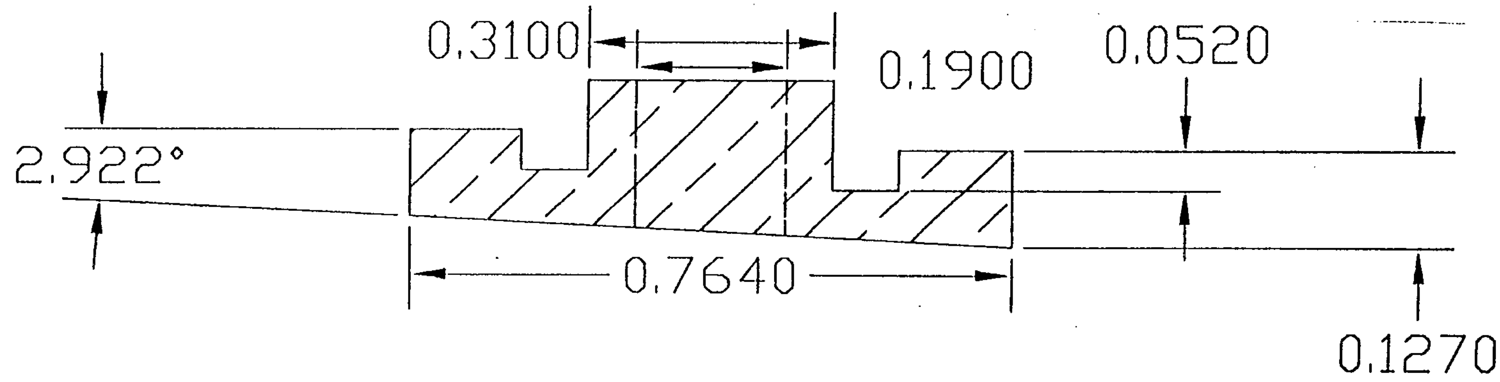
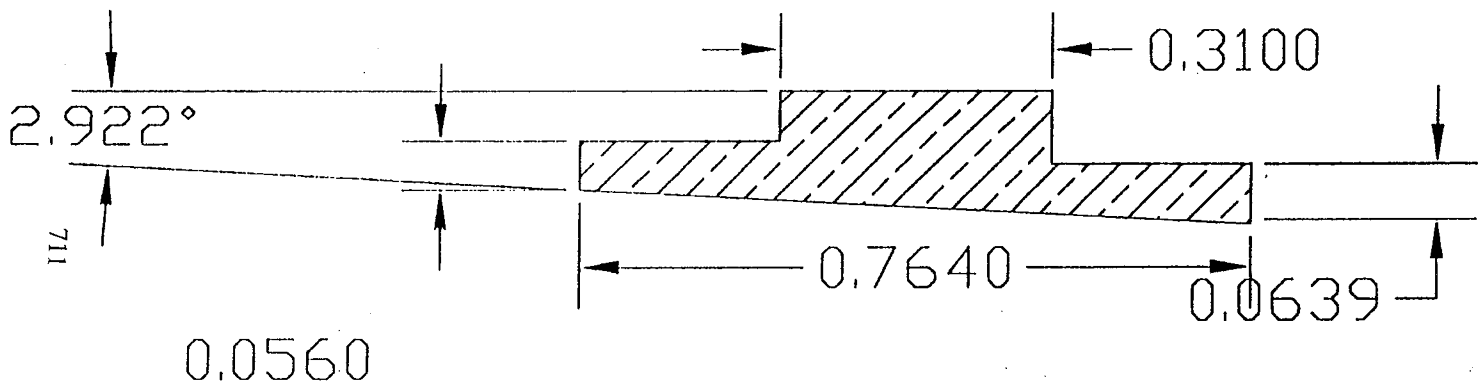
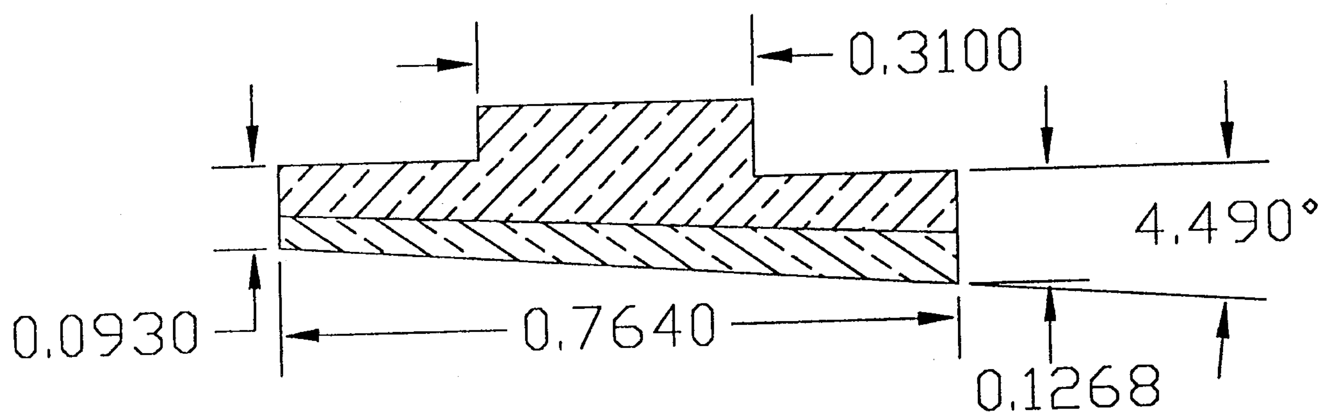
T55-L-712 AXIAL COMPRESSOR TIP CLEARANCES WITH MAGNESIUM SHROUD

STAGE	COLD BUILD CLEARANCE	AVERAGE RUNNING CLEARANCE
1	.019-.029 in.	.016 in.
2		.020 in.
3		.017 in.
4		.022 in.
5		.026 in.
6		.028 in.
7		.027 in.







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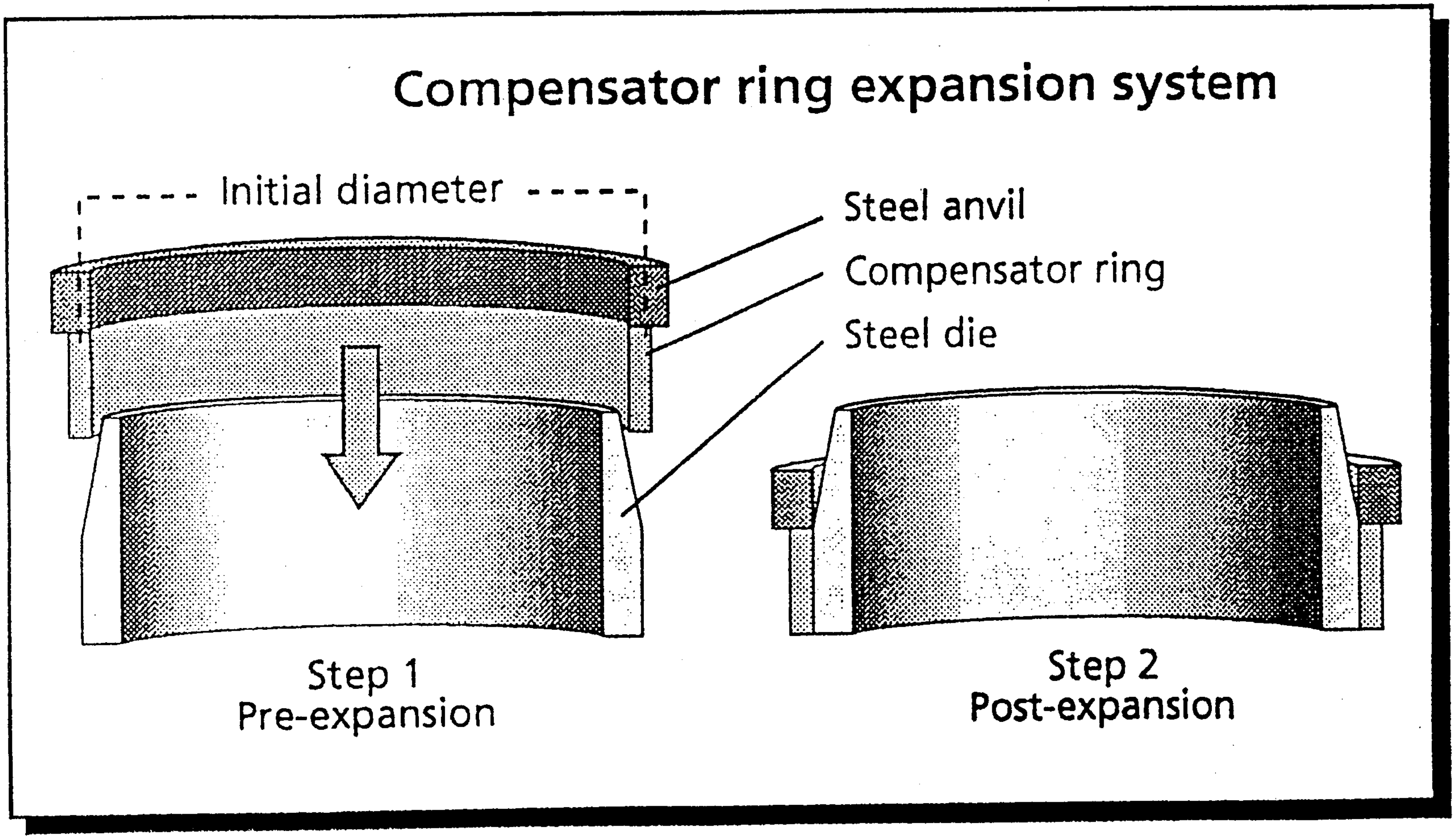
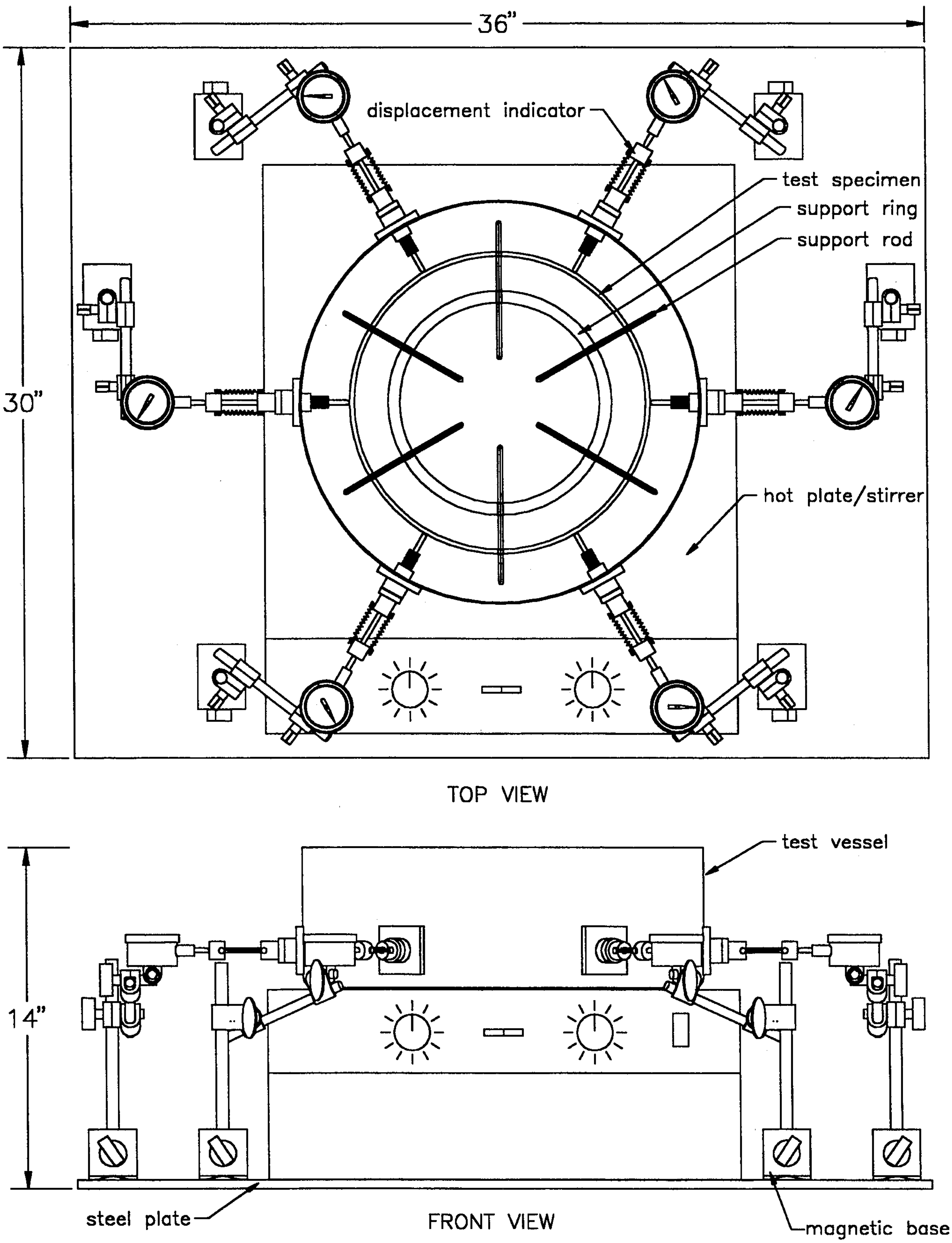
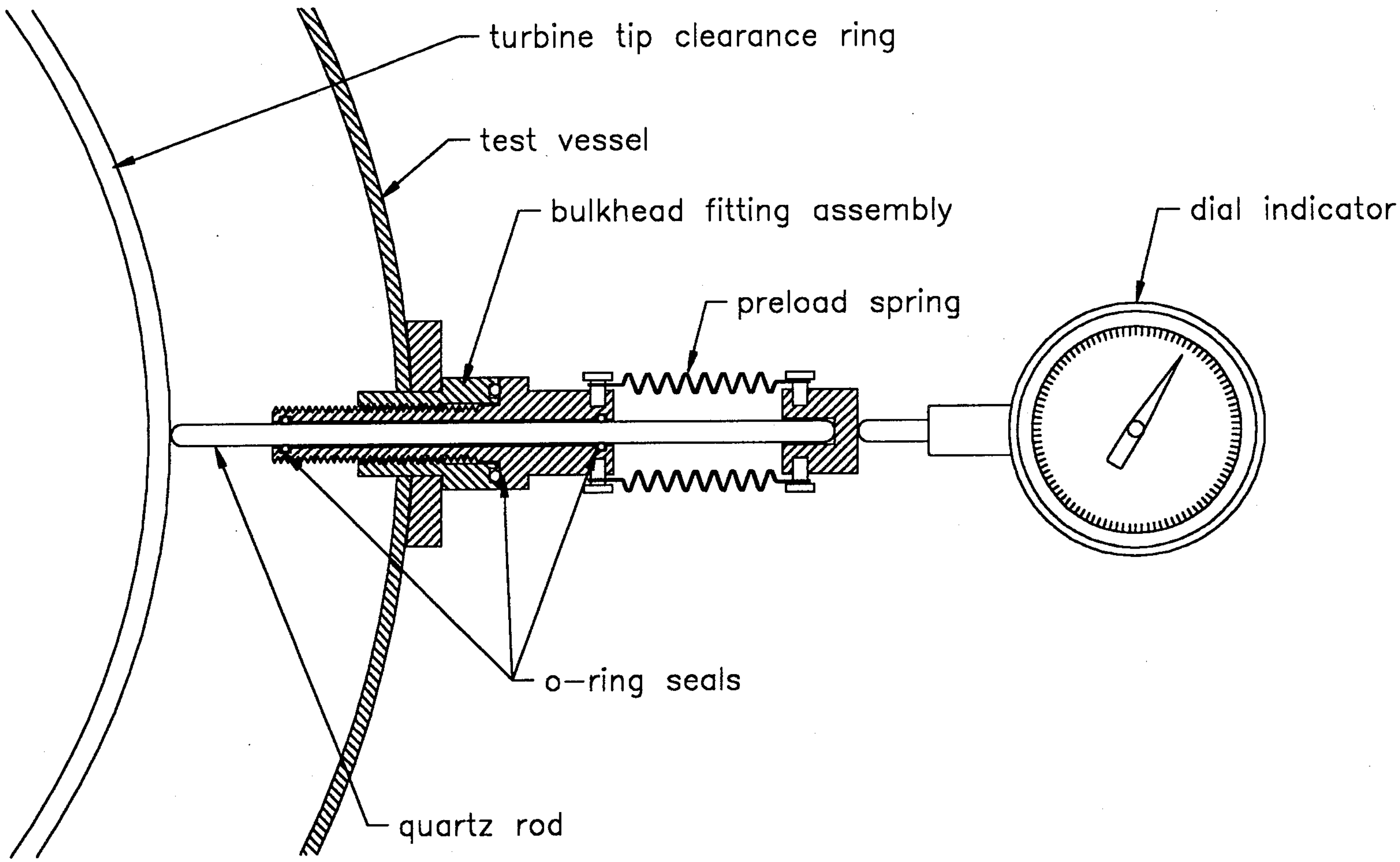

Compensator ring expansion system
Initial diameter
Steel anvil
Compensator ring
Steel die
Step 1
Pre-expansion
Step 2
Post-expansion



TEST APPARATUS FOR TURBINE TIP CLEARANCE RING



DISPLACEMENT INDICATOR (SECTIONAL VIEW)

TABLE 1

Location	Type	Purpose
Inlet	6 Pt 4 Tt	Inlet P, T for referral
Bellmouth	4 Δp 6 Tt	Actual flow
Axial Compressor	4 Ps 0W stages 1-7 Pt 3x5 radii stages 1,2,3 Tt 3x5 radii stages 1,2,3 Pt 3x3 radii stages 4-7 Tt 3x3 radii stages 4-7	Ps for stage headrise characteristics. P,T,Ps for stage - stage performance based on integrated flow
Compressor Exit	Pt 8x4 radii Tt 8x4 radii Ps 9 iw 11 ow	η,Pr,Tr, overall compressor performance.

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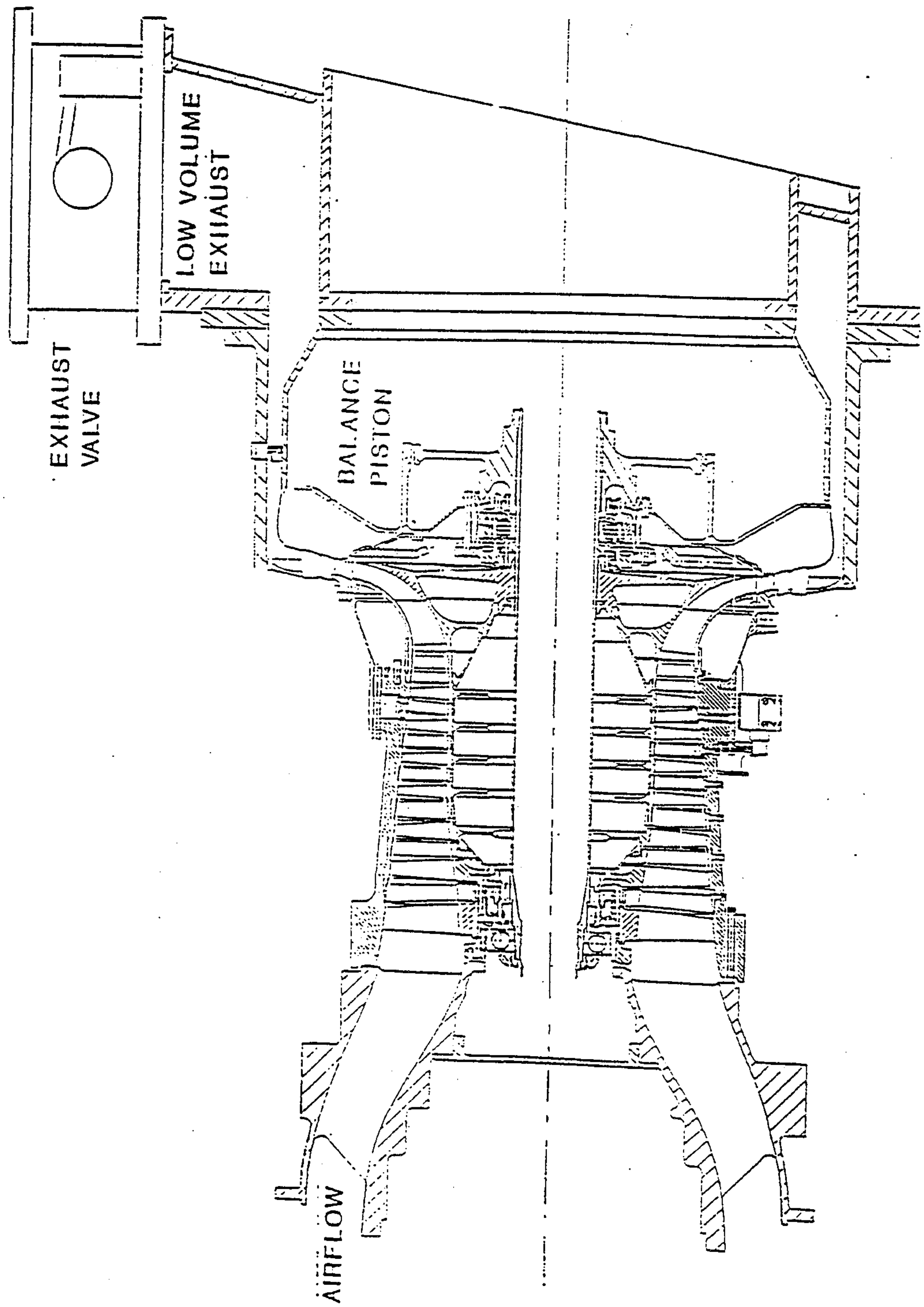
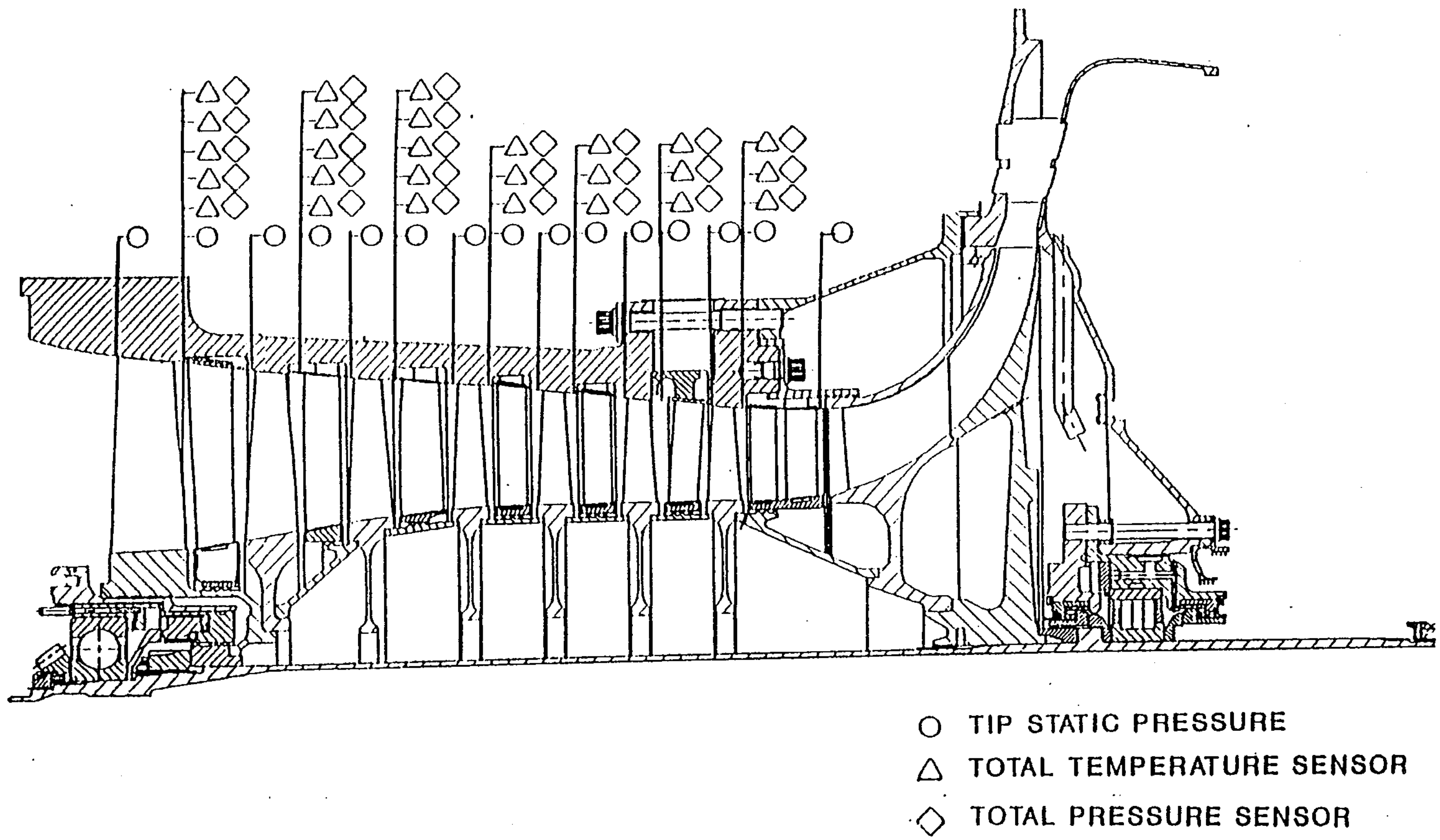

EXHAUST VALVE
LOW VOLUME EXHAUST
BALANCE PISTON
AIRFLOW



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